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# Smart Structures for Rocket Propulsion Systems

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## ABSTRACT

Solid and liquid propellant rocket propulsion systems are weight and performance driven machines whose components experience extreme environments. However, the structural integrity of both types of propulsion systems is currently monitored through type testing, labor-intensive x-ray analysis, and other NDE techniques. Smart structures technologies have the potential not only to alleviate some of the maintenance burden of current rocket propulsion systems but also improve the capability of future systems. This paper discusses the rocket design parameters and operational environments driving the application of passive structural health monitoring systems to both liquid propellant engines, with complex rotating machinery and severe thermal environments, and solid rocket motors, with long required silo lives of highly filled, chemically active, viscoelastic propellant. The potential for application of active smart structures technology to rocket systems will also be discussed including the control of solid propellant to permit throttling of solid motors and control of thermal shrinkage, vibration suppression, and improved creep resistance of rotating components and subassemblies for liquid rocket engines. While the rocket manufacturers are not currently developing smart structures technology for propulsion applications, the potential improvements in increased systems reliability, longer operational lifetimes, reduced weight, increased capability drive the need for research in this area.

## ROCKET PROPULSION INTRODUCTION

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does LRE stand for 'Liquid propelled rocket engine' or just 'liquid rocket engine?'

There are two basic families of rocket propulsion systems, grouped by type of propellant employed: Liquid propelled Rocket Engines (LREs) and Solid propellant Rocket Motors (SRMs). The sizes of either type of system are indicated by their thrust rating, or force delivered by the system at sea level. Rockets in both families vary from very small (6 lbs thrust) divert thrusters and satellite propulsion systems to very big (60,000 lbs thrust) launch vehicle boosters. Other families of rockets also exist, such as hybrid engines, (which employ both solid and liquid propellants), solar, and nuclear fueled rockets. However, no currently fielded systems employ engines from these other



* lb not lbs

Distribution statement

families. Electric propulsion systems do exist in large-scale production for satellite applications, but their design parameters are significantly different than those of solid and liquid booster systems. Therefore, this paper concerns itself with the application of smart structures technologies to the commonly fielded rocket propulsion systems of LREs and SRMs.

## Liquid Rocket Engines (LREs)

Liquid engines range in thrust level from 0.2 lbf thrust hydrazine monopropellant thrusters for satellite attitude control systems[1] to 650,000 lbf thrust launch vehicle engines.[2] Their sizes range from less than 6 inches long and 0.73 lbm for the MR103C engine to 180 inches long and 14,000 lbm for the RS-68. The extremely small attitude control thrusters are generally monopropellant systems employing simple valving to control the flow of propellant and a catalyst bed to generate propulsive gas from the storable propellant. The large booster engines, like the space shuttle main engine (SSME) and RS-68, rely on elaborate turbine driven pumps to control the flows of the cryogenic liquid propellants.[3] Propulsive gases are generated by combustion of the propellants in a regeneratively cooled thrust chamber. The hot gases are then expanded through a regeneratively cooled nozzle and radiatively cooled exit cone.

The extremes of the liquid engine environment create challenges for the application of smart materials to rocket systems. Tankage, ducting, and pumps operate with design factors of safety as small as 1.5 at cryogenic temperatures. Turbines, combustion chambers, and nozzles operate in the combustion gases at stress levels close to yield. The extreme thermal shock environment, vibration, and drive to minimize component weight have lead to designs employing monolithic, high stiffness, high specific strength materials. While research is continuing to develop ceramic and metal matrix composites for liquid rocket engine components, most components are made of wrought, forged, or cast titanium, aluminum, or nickel-based superalloys. The weight and structural criticality of LRE components along with the stiff, monolithic nature of the materials, and reliability requirements make it difficult to envision smart materials in liquid rocket propulsion systems.

## Solid Rocket Motors (SRMs)

Applying smart materials technologies to solid motors presents a different set of challenges. Solid motors can be as small as the 2 in long, 2 lbf thrust Estes A motors[4] or as large as the 149 ft long, 3.3 million lbf thrust Space Shuttle Solid Rocket Booster (SRB).[5] Solid propellants are, generally, highly filled elastomers that carry load as well as create intimate contact between the aluminum fuel and ammonium perchlorate oxidizer particulates. The solid propellant is encased by polymer matrix composites in many expendable boosters or by metal pressure vessels in the cases of air-launched missiles and the reusable SRBs. Propulsive gases are generated by combustion of the solid propellant and these gases often entrain a significant amount of solid particulates and molten aluminum. The pressurized propulsive gases are accelerated through ablative carbon/carbon nozzles to produce thrust.

In general and unlike LREs, SRMs have very few moving parts. They tend to be expendable systems in which low cost, low inert weight, and high reliability are design drivers. Mid-sized air-launched missile propulsion systems have unusual operational requirements that frequently drive material selection and design. Air-launch systems have maximum allowable outer dimensions and must survive temperature soak conditions from –65 F to 165 F as well as cook-off (survivability in an open fire) and bullet impact safety tests. Extremely long "on-alert" storage lives influence the design and refurbishment requirements of large ballistic missile propulsion systems, although their thermal environments are benign. The long life cycles of currently operational solid rockets, the chemical activity of the propellant, and the volume limitations on many solid propulsion systems create challenges for applying smart materials technologies to solid rocket motors.

## CURRENT STATE-OF-THE-ART

The application of smart materials technologies to rocket propulsion systems in the operational environment is still in its infancy. Fiber optic strain and vibration sensors that were developed in Universities two decades ago are just now being tested in components of health monitoring networks in operational systems. At the moment, these passive sensors are used only to alert operators to harmful conditions. The data are not used to control or optimize engine performance, nor are sensors imbedded in the engine components. The extreme conservativism of the rocket industry's engineering process has been one of the hurdles to be negotiated for application of any new technology. However, the infrastructure necessary to support the use of active materials technology is now being developed by the operational community: Development of smart materials technologies for rocket propulsion systems will continue.

Several factors have made the application of passive health monitoring technologies to rocket propulsion systems possible. The maturation of the Space Shuttle as a means of reliable access to space has focused research attention on system reliability, predictability, and operational costs: areas where health monitoring technologies demonstrate high payoffs. Advances in computational technologies and performance modeling have helped to define baseline operating conditions for comparison with sensor data. Instant data acquisition and analysis, reduced size and weight of data storage, and wireless data communication permit networks of sensors to be interrogated and the data interpreted in real time. The development of specialized sensors and demonstrated ruggedness of sensors has allowed specific information to be collected within the operational launch vehicle environment. Because of their potential to increase reliability and reduce maintenance costs, many passive sensor technologies are being developed for reusable liquid propellant launch vehicles. Because SRMs have few moving parts and are usually expendable, few sensing technologies are being developed for solid missiles and boosters. While the application of passive materials sensing technologies is beginning, development of active materials systems is slow.

There are impediments to continued advancement toward smart materials application. The lack of design practices and system integration tools is one of the largest impediments to application of smart materials. Two other impediments thwart the progress of many technologies: a lack of demonstrated reliability in operational environments and a paucity of realistic demonstration articles on which to demonstrate reliability. Similarly to reliability, the non-interference of active material systems with other components and systems in the rocket must be demonstrated. Overcoming these impediments is essential to the acceptance of smart materials technology in the operational environment.

## LREs

Although originally developed from 1960's technology, the Space Shuttle Main Engines[6] are the state-of-the-art in operational liquid rocket engines for launch vehicles. Continuous upgrade programs integrate new technologies safely into the SSMEs to increase performance and improve reliability. One of NASA's current upgrade programs is the IVHM, or Integrated Vehicle Health Management project[7] which includes the Advanced Health Monitoring Systems for the SSME, as well as monitoring systems for other parts of the Orbiter.[8] The AHMS for the SSMEs includes spectrometers to detect anomalies in the engine exhaust plume[9] and accelerometers to monitor turbopump vibration. Aspects of the health of the Orbiter are monitored by MEMS hydrogen gas sensors[10], which detect fuel leaks, and remotely monitored temperature sensors.[11] Neural network architectures collect and interpret sensor data. Although rudimentary from the smart materials perspective, these health-monitoring devices are being flight-tested and are gaining acceptance in the operational community. Recent acquisition programs have requested plans for development of exit cones with self-healing characteristics and plans for demonstrating health management technologies are being developed. Programs to investigate advanced turbine blade vibrational damping and advance engine component demonstrations are being planned through the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program for 2005. While the current operational LREs are beginning to test passive "smart materials" technologies, there is a significant amount of interest in active materials research aimed at improving reliability, optimizing performance, and reducing maintenance requirements for LREs.

## SRMs

Application of passive sensing technologies to SRMs has been slower than for LREs. The utility of developing specialized systems for expendable motors has been questioned. Solid rocket boosters have yet to apply health-monitoring systems in the operational environment. Studies have shown that fiber optic strain gauges can be embedded in composite solid rocket motor cases without detriment to their structural integrity.[12] However, such systems have not found acceptance in the operational community. Solid propellant itself could be considered an active material and research is continuing into controlling the aging and performance of solid propellant. Several specialized materials systems have been tested to permit air-launched missiles to pass cook-off tests, but these systems are not generally in operation in American missile systems. However, planning for next generation ballistic missiles includes efforts to develop health-monitoring systems. Overall, the interest in smart materials research in the solid motor community is more specialized and fragmented than in the LRE community.

## POTENTIAL APPLICATIONS OF SMART STRUCTURES TECHNOLOGIES

Smart structures technologies imply not only the ability of a component to sense its condition and changes in its condition, but also the ability to assimilate data from other sources, and effect the condition or geometry of the structure. This complicated set of activities was demonstrated a decade ago using strain gauges and piezoelectric actuators to damp vibration of a polymer matrix composite beam. Smart structures exist. Further evolution of smart materials technology requires adaptation of the technology to stiffer, more highly loaded structures that operate more extreme environments with high reliability. Distributed networking, information processing and continued miniaturization of data transmission and memory devices will also be required. A few potential applications of evolved smart materials technologies are listed here to illustrate the needs of the community.

LREs

Proximity and shrinkage sensors for cryogenic components: The turbopumps that pressurize and control the flow rate of propellants shrink significantly when chilled to cryogenic propellant temperatures. Modeling and computational predictions of this shrinkage have not been validated on operational components. Embedded sensors that could verify the shrinkage of cryogenic components without interfering the engine performance would be helpful to engine development. Similarly, questions exist about the size, shape, and flow through narrow passages in the cryogenic pumps during test. Sensors that could verify the proximity of one surface to another during operation without interfering with engine performance are also needed. The data could be used for code validation as well as engine design verification.

Suction performance control: Deep throttling and changes in propellant pressure from the supply tanks require different performance characteristics in the pump. One of the performance characteristics, suction, is controlled by the clearance between the impeller blade and the pump housing. A smart impeller blade that could control this clearance with length changes of small fractions of its depth could alleviate poor suction performance in deeply throttled engines. Impeller blades are typically made of titanium, aluminum, or nickel alloys and operate at 50,000 rpm at cryogenic temperatures. Changes of 0.13 inch on a blade that is roughly 2 inches deep and 0.25 inch thick would be required. A deeper thrust throttling range and optimal pump performance at any thrust level would result.

Vibration control of turbomachinery: Rocket engine turbines, impellers, and pumps often operate between structural harmonics, both of the blades and the shafts. Normal operation requires that the structures pass through their resonant frequencies while coming up to full power or while throttling. Active vibration control in the turbine and pump blades and shafts could alleviate transients, rub, and fatigue damage to turbomachinery. Turbines are frequently made of nickel-based superalloys and are driven to 50,000 rpm by hot oxygen or fuel-rich combustion gases. Impellers and pumps control cryogenic fluids, as mentioned above. Shifts in frequency of 1000 Hertz continuously during operation may be required. Being able to shift the resonant frequencies of pump and turbine blades and shafts would increase engine reliability and reduce maintenance requirements.

Health and performance monitoring: As mentioned earlier, structural health monitoring systems in rocket engines are in their infancy. Imbedded sensors and active materials whose outputs optimize engine performance and trigger maintenance actions are being developed. Many parameters important to optimizing engine performance could be measured or controlled, such as: coolant flow for transpiration or film cooling, propellant temperatures and flow rates, component temperatures, fatigue and environmental cracking, component shrinkage, and vibration.

Nozzle actuation: The direction of the thrust vector is controlled by gimbaling of the nozzle or the entire engine. Mechanisms to direct the thrust vector by warping the exit cone or optimize exhaust performance by changing the shape of the exit cone would be interesting. However, exit cones are typically fabricated from carbon or ceramic matrix composites and must survive the operational exhaust gases, the space environment, and reentry. However, the weight of nozzle actuation systems could be substantially reduced if distributed nozzle warping materials could be developed.

Self-healing exit cones: Exit cones on reusable vehicles must survive extremes in temperature and pressure during each mission while maintain structural integrity and impermeability to exhaust gases. Reusable exit cones must also survive the vacuum of space, reentry, landing, and engine refurbishment. With the extreme thermal shock, vibration, temperature gradients, and chemically active gas erosion environments in the exit cone, matrix cracking is inevitable. Mechanisms that heal small cracks in the matrices of ceramic matrix composite could improve the performance and reliability of liquid launch vehicle engines.

SRMs

Non-eroding throats: Current solid rocket propulsion systems must be designed to compensate for the loss of performance due to throat erosion. Multiphase flow of chemically active gases and hot aluminum particulates erode the carbon/carbon composite or tungsten throats of solid rocket motors during operations. Active materials that could compensate for throat erosion would improve performance of solid propulsion systems.

Nozzle actuation: Similarly to LREs, the thrust vectors of SRMs are controlled by gimballing the exit cone. Active materials that could direct the thrust vector by warping the carbon/carbon exit cone would reduce the system weight by removing the gimballing structure and actuators and improve reliability by reducing parts count.

Damage detection: Polymer composite motor cases are susceptible to damage during transport and handling. Reliable, long term damage detection mechanisms are constantly being researched.

Propellant aging, self-healing, and bondline repair: Solid propellant is a chemically active filled viscoelastic material. Mechanisms are being sought to detect the chemical changes that occur within the propellant which make it unsafe or ineffective. Cracks develop in the propellant and in the bondline between the propellant and insulation over the decades large motors are in silos. Active propellant that could repair small cracks or indicate when performance is impaired would decrease maintenance costs and improve system reliability.

## SUMMARY OF RESEARCH NEEDS

In examining these potential applications as a whole, several research needs become apparent, if these technologies are to be applied to rocket propulsion.

System modeling and performance prediction: To apply an active material to a component, the behavior of that component must be understood with a high degree of accuracy. One must know what it is that the active structure is to do. The structural and performance modeling of rocket components necessary to understand required behavior is not well developed or experimentally validated. The behavior of active materials themselves is not always straightforward to model and design techniques for applying active materials to components are not in practice. Design methodologies for active systems are not generally taught in the current curriculum. Therefore, further application of smart material technologies will require improvements in predictive tools, design methods, and system integration tools.

Data communication: Accurate wireless data communication that is physically non-intrusive, does not interfere with electrical or chemical systems, and is not interfered with by the operational systems or the space environment are required to coordinate the actions of different smart materials to effect a single outcome. Additionally, data from a propulsion system must be communicated in spite of the engine vibration environment, metal components, and proximity to potentially explosive propellants. Therefore, research into methods of relaying information real-time is necessary.

Stiff material actuation systems: Monolithic metals, ceramics, metal matrix composites, and ceramic matrix composites are the materials of choice for many rocket components. Embedded sensors must survive the processing of these parent materials. Active systems for stiffness and geometric control of components must actuate high-stiffness cross sections in extreme environments. Development of powerful, robust actuation systems is necessary.

Reliability: Unmanned rocket systems are generally designed with factors of safety of 1.25. These low factors of safety and demands for high system reliability require highly repeatable, predictable, reliable material behavior. Active materials must be well characterized and dependable before they can be applied to operational systems.

Responses other than shape change: Most currently available active materials change shape or stiffness on command. Several of the applications mentioned above require "self-healing" materials that can close, fill, or arrest cracks and porosity. Since mass can not be spontaneously created within the material, other mechanisms to heal materials in a distributed manner on demand must be developed.

Data interpretation and decision routines: Translating sensor data into understandable information requires solutions to inverse problems with no closed form solutions. Many solution routines are computationally intense and will not result in accurate real-time solutions. Data are noisy and frequently different sets of information are needed to base an actuation decision. Distributed and interacting decision centers may also be useful for total system control. Therefore, research into fast problem solving routines and noisy data interpretation is also necessary.

## CONCLUSIONS

The application of smart materials technologies to rocket propulsion systems is in its infancy. Current research efforts are focused on developing useful, reliable, and cost-effective passive health monitoring systems for both liquid rocket engines and solid motors. However, as the ability to embed sensors and actuation devices into stiffer and more rigorously processed materials develops, there will be significant pay-offs for active materials technology in rocket propulsion.

## ACKNOWLEDGEMENTS

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